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A SIMPLE PREDICTION METHOD FOR THE SIGNAL DETECTABILITY OF ACOUSTIC SYSTEMS

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A SIMPLE PREDICTION METHOD FOR THE SIGNAL DETECTABILITY OF ACOUSTIC SYSTEMS

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ABSTRACT: A method is given for predicting the signal-to-noise ratio to be expected for some simple receiving systems. The method relies heavily on the work of Peterson, Birdsall and Fox, and requires, as a starting point, a specification of detection and false-alarm probabilities as performance criteria. Some sonar examples are indicated, and the validity of the method is demonstrated by comparison with measured recognition differentials for the ear, and with measured detection thresholds for A-scan radar displays.

For sinusoidal signals in Gaussian noise, the minimum achievable signal-to-noise ratio is shown to be $d/2T_s$, where d is determined by the selected probabilities and T_s is the observation time. This minimum threshold deteriorates whenever the system requirements impose a deterioration of knowledge of the signal. It is clear that in general the only valid approach to improving the detection threshold is to improve the available knowledge concerning the signal and noise.

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This is a joint report by NOL and ONR (Code 411) on a subject of vital concern to sonar system designers. It presents, for the first time, simple formulas for predicting the input signal-to-noise requirements of detection systems. It demonstrates that simple, well-known detection techniques often do as well, signal-to-noise-wise, as more sophisticated methods. The NOL portion of this work was funded under Task No. RUDC-5E622/212-1/F001-13-005, "EER Signal Processing". This report will be of interest to scientists and engineers concerned with designing or evaluating signal processing systems.

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Z. I. Slawsky

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By direction

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INTRODUCTION

Any detection device, whether it be as complex as a digital computer or as wonderful and compact as the human ear, requires a minimum input signal-to-noise ratio for successful operation. This minimum acceptable signal-to-noise ratio is of immediate and vital concern to the design engineer, because it is one of the parameters that determine system performance. Yet the engineer concerned with devising new systems or understanding the behavior of old ones has had only limited and often ad hoc means for predicting the signal-to-noise ratio for any detection device of interest, and he has not ever been sure about what system parameters must be known or specified for the purpose.

During the past decade, a great volume of work has been done on information theory, decision theory and detection theory. In particular, the work of Peterson, Birdsall and Fox(1), and Van Meter and Middleton(2), has provided the necessary theoretical basis for predicting what input signal-to-noise ratio will be required for a detection device, once certain performance criteria are decided upon. The usefulness of decision theory in sensory measurements has been brought out in audition by Tanner and Swets(3), and in vision by Swets, Tanner and Birdsall(4). The present paper attempts to provide the design engineer with a method of estimating the required input signal-to-noise ratio, for a receiver using all the available knowledge of the signal and noise and satisfying certain performance criteria. Although such a computation will apply strictly to a receiver utilizing the information available to it in the most statistically efficient manner, theory and examples suggest that many receivers, including the human ear, do not fall far short of this ideal receiver in actual performance.

In underwater sound, the input signal-to-noise ratio expressed in db required for detection is commonly called the "recognition differential" of the receiver. This term was borrowed from the theory of audition, where it refers to the "differential" needed to "recognize" a tone presented to the ear in a noise background. In the underwater sound literature this somewhat unfortunate term is commonly defined as the signal-to-noise ratio required to detect a signal a certain specified fraction of the time (usually 50%, although other detection probabilities have been employed). It is now recognized, however, that this definition is incomplete, and therefore quantitatively meaningless, because it fails to specify the percentage of false signals or "false alarms" that are permitted to occur. These "false alarms" are a vital and determining factor for recognition differential. Indeed, any signal, however small, can be detected an arbitrary percentage of the time (including 100%) if the number of false alarms is allowed to increase indefinitely. For this reason, nearly all of the older literature is not immediately useful from a quantitative standpoint, inasmuch as the false alarm rate seldom appears to have been determined.

A term equivalent to, but more general than recognition differential is detection threshold.* This may be defined as the input signal-to-noise ratio required for detection for specified values of detection and false-alarm probabilities. Detection threshold is most conveniently referred to a one cycle per second bandwidth of noise; when the signal itself is noise-like in the sense that its power is distributed over a band of frequencies, it too will be referred to a one cycle per second bandwidth. Thus, for single frequency signals of power S occurring in a noise background of spectrum level N_0, the detection threshold is the ratio S/N_0; for band-energy signals of spectrum level S_0, it will be the ratio S_0/N_0. In all cases, the spectrum levels referred to will be those in the input band of the detection device.

The general approach of this paper to predicting the detection threshold is to begin with a specification of the performance that is desired from the detection system. In terms of detection, this performance can be completely specified by means of two parameters: 1) the detection probability, or probability that a signal, when present, will be detected, and, 2) the "false alarm" probability, or probability that a signal, when absent, will be (falsely) detected. These two probabilities must be determined by the nature of the use to which the detection system will be put, and the values and costs involved in decisions resulting from the operation of the system. Having selected these two probabilities, the next step is to refer to an appropriate set of ROC (Receiver Operating Characteristic) curves developed[5] from basic statistical considerations of signals and noise, and to read therefrom a value of a parameter, d. Having selected this parameter, simple expressions are used to relate the input signal-to-noise ratio required for detection under the conditions selected at the outset (the detection threshold) to 1) the bandwidth of the receiver, W, 2) the duration (pulse-length) of the signal T_s, 3) the integration time of the post-detector smoothing filter, T, and 4) the type of detector employed. As illustrations of the method, comparisons will be

*Not to be confused with the processor output "threshold", of reference (1).

given between the theoretical performance computed in this manner and the observed thresholds of two systems. One is the ear, which, if assumed to behave as an energy detector according to the aural critical band model, is found to have a recognition differential in approximate agreement with the theoretical model. Another example is provided by radar detectability data of pips on an oscilloscope screen, for which the method gives excellent predictions of observed thresholds.

DETECTION THRESHOLD FOR SIMPLE CASES

In 1954, Peterson, Birdsall and Fox(1) published a general theory of signal detectability utilizing detectability criteria in its basic approach. In this approach a receiver is judged on the basis of its conditional probability of detection if a signal occurs at its input, P(D), and on the conditional probability of a (false) alarm if no signal occurs, P(FA). The detection and false alarm performance of any receiver can be summarized in one graph, called a Receiver Operating Characteristic (ROC), in which P(D) is plotted against P(FA). For an optimum receiver utilizing all the information available to it the parameter "d" of the ROC curves is found to be simply related to the signal-to-noise ratio at the receiver input.

In applying the theory to practical problems, Peterson, Birdsall and Fox recognized a number of cases involving different degrees of knowledge concerning signals in Gaussian noise backgrounds. Three of these we may call Cases I, II, and III. Case I applies for a signal waveform known exactly in a background of white Gaussian noise. Case II is that of a signal known exactly except for phase, also in white Gaussian noise. Case III applies strictly for a Gaussian noise-like signal in a background of Gaussian noise; all we know about the signal is its mean and its variance as a Gaussian sample. For underwater sound, Case I would apply for echo ranging in an ideal medium on a stationary target at an exactly known distance, or for communication over a fixed known distance. Case II is, for example, that of ordinary echo ranging on a target of slightly unknown range*, where the time of occurrence (phase of the echo carrier is unknown; Case III applies for echo ranging with noise pulses or explosives where

*When the range, or time of occurrence, is completely unknown and may fall within any one of M non-overlapping range intervals, the echo may be said to be one of M orthogonal signals. It can be shown that the detection threshold is then $S/N_0 = \frac{d + \ln M}{2T_s}$. This, and other cases of sonar and radar interest, are treated theoretically by Peterson and Birdsall(5).

$WT_s >> 1$. The ROC Curves for Case II are similar to those of Case I, but have values of d approximately twice those for Case I in the usual working range of P(D) and P(FA). The ROC Curves for Case III can be shown to reduce to those of Case I when the input signal-to-noise ratio S/N is small and when the number of sample points $2WT_s$ is large. Figure 1 shows the appropriate set of ROC Curves applying to these cases, which represent successively greater deterioration of knowledge concerning the signal.

For Case I, d is related(1) to the system parameters through the definition $d = \frac{2E}{N_o}$, in which E is the energy of the signal, equal to signal power S times signal duration τ, and N_o is the noise power per unit bandwidth, equal to N divided by W. Hence we have

$$d = \frac{2S\tau}{N/W} = 2WT_s \cdot \frac{S}{N}$$

where $\frac{S}{N}$ is the signal-to-noise ratio in the receiver input bandwidth W. Hence for these cases the detection threshold is

$$S/N_o = \frac{d}{2T_s}$$

For Case II, d is about twice its value for Case I, so that

$$S/N_o \approx \frac{d}{T_s}$$

These two cases imply the use of coherent processing in which the detailed information about the signal is utilized in the processing circuitry. For Case I, where the signal is known exactly, it can be shown that the optimum processor is a cross-correlator in which the input signal plus noise is correlated with a replica of the completely known signal. For Case II, the optimum processor is again that of a Case I cross-correlator; however, lack of phase information requires two such processors in quadrature. Higher detection thresholds (about 3 db) are required in Case II than in Case I, as would be expected from the fact that less information is required about the signal in Case II than in Case I.

For Case III, Peterson, Birdsall and Fox show that the ROC Curves of Case I apply, provided that d be taken such that $d = WT_s (S/N)^2$ under the conditions that $S/N << 1$ and $2WT_s >> 1$. These are the usual conditions of interest. For sinusoidal signals in Gaussian noise, the detection threshold becomes

$$S/N_o = \left(\frac{dW}{T_s}\right)^{\frac{1}{2}}$$

Since essentially only the signal energy is known, the optimum type of processing is an energy detector, such as a nonlinear detector or amplifier, preceded by a filter. It can be shown that the optimum likelihood-ratio detector is a square-law detector, having an output proportional to the square of the input. Other types of non-linear devices — such as the full-wave and half-wave linear rectifiers -- have a detection performance somewhat poorer than that of the square-law detector. Table I is a summary of the detection threshold for the three simple cases considered, together with values of the factor k representing the efficiency of a particular nonlinear detector. For Gaussian noise-like pulses, it is often convenient to express the input signal-to-noise ratio in terms of both signal and noise in a one-cycle band, so that the detection threshold becomes

$$S_o/N_o = \frac{S}{WN_o} = \left(\frac{kd}{WT_s}\right)^{\frac{1}{2}}$$

So far, we have not considered the effect of any post-detector averager or smoothing filter that may be included in the detection process, such as considered in reference (6), for example. If a post-detector smoothing filter of integration time T is used, the above holds only if $T = T_s$. If $T > T_s$, too much smoothing is used; the pulse does not build up to its full value and the detection threshold increases. If $T < T_s$, insufficient smoothing is used; the pass band $\frac{1}{T}$ of the filter is excessively broad and too much noise reaches the output. The effect of a mismatched output filter is to add the quantity $|10 \log T/T_s|$ to the detection threshold in decibel units for Cases I and II, and $|5 \log T/T_s|$ for Case III. Similarly, if n incoherent presentations are made, the expressions for detection threshold in db should include a term -10 log n in Cases I and II and -5 log n in Case III.

Before considering specific examples, it may be worthwhile to consider the meaning of these expressions for the design engineer who strives to minimize the signal-to-noise requirement for his system. The formulas just given verify the well-known precept that it is always desirable to use the largest T_s compatible with other requirements, such as range and range resolution. A second requirement is that the integration time T of the output averager must be made equal to T_s. Finally, the input bandwidth must be made as small as possible compatible with other requirements (such as the bandwidth needed to accommodate Doppler shift), although it must not be smaller than approximately $1/T_s$. The essential aspect of the matter is that <u>the minimum signal-to-noise ratio required for detection is determined by the available knowledge concerning the signal and noise</u>. When this knowledge is complete, as it is for the case of an exactly known signal in

TABLE I

DETECTION THRESHOLD IN GAUSSIAN NOISE

	Optimum Processing	Detection Threshold
Case I Signal known exactly	Cross correlation of signal plus noise	$S/N_o = d/2T_s$
Case II Signal known exactly except for phase	Same, but with multiple time delays	$S/N_o \approx d/T_s$
Case III Signal energy known (sinusoidal signals)	Non-linear detection	$S/N_o = (kdW/T_s)^{\frac{1}{2}}$
	square law detector	$k = 1$
	full-wave rectifier	$k = 1/(\pi - 2)$
	half-wave rectifier	$k = \dfrac{1}{2\pi - 2}$

Gaussian noise, a certain minimum signal-to-noise ratio can be achieved. As the knowledge concerning the signal deteriorates (as when the signal frequency is uncertain because of the Doppler shift produced by a target moving at an unknown speed), the signal-to-noise ratio also deteriorates. This behavior of the detection threshold with deterioration of information about the signal is shown in Table II, where a number of instances of successively decreasing knowledge concerning the signal are listed. The second column in the table gives the conditions applying for sonar echo ranging when the knowledge about the phase (time of occurrence), frequency, and pulse length of the echo successively deteriorates. By way of illustration, the column on the right gives a numerical example of the achievable detection thresholds for one set of selected values of the determining parameters.

Another way of illustrating the subject is shown in Figure 2, where the increase in detection threshold over that required when the knowledge of the signal is complete is plotted as a function of WT_s. If, for example, it is necessary to use a WT_s product of 100 and a T/T_s ratio of 4 (or $\frac{1}{4}$) in order to satisfy the requirements of the system, then $13\frac{1}{2}$ db more signal will be required for detection over what would be needed if the echo were known exactly. This is the penalty that must be paid for the failure, caused by system requirements, to take advantage of all the characteristics of the signal.

When the signal is known completely, a delayed, noise-free replica of the signal can be generated and fed into a cross-correlator; this provides the optimum detection system. Alternatively, a square-law detector, preceded by a matched filter and followed by a matched averager, is a detection system having the same detection threshold. This is evidenced by Figure 2 in the vicinity of $WT_s = 1$. Indeed, for pulsed sinusoidal signals the minimum threshold can be achieved if WT can be made equal to unity; in this case all processors are equivalent.

It may have been noted that we have not made mention of an output signal-to-noise ratio, or of the processing gain achievable in detection systems. Instead, the output of the system is considered to be the detection decision itself, as determined by decision theory involving selected probabilities concerning the presence of a signal or its absence. In this view, the basic measure of processor performance is the parameter d of the ROC Curves. Comparison of the d for Case I with that needed to achieve the same P(D) and P(FA) with a less efficient processor (one designed using less than complete knowledge of the signal, for example) results in an efficiency-measure of the less efficient process. This efficiency is expressed as the increase in

TABLE II

EXAMPLES FROM SONAR

Knowledge Concerning the Signal	Sonar Example	Numerical Example:* 10 log (S/N_0)
Signal known exactly	Echo from a fixed point target at a known range	+15
Signal known exactly except for phase (i.e. time of occurrence)	Echo from a fixed point target at a slightly unknown range	$+17\frac{1}{2}$
Signal frequency unknown	Echo from a moving point target at an unknown range	+19 $(T = T_s)$
Both signal frequency and duration unknown	Echo from a moving, extended target at an unknown range	$+20\frac{1}{2}$ $(T = 2T_s)$

*Parameters chosen for the example are:

$p(D) = 0.5$, $p(FA) = 0.05$, $T_s = 0.05$ sec, $W = 100$ cps, $T/T_s = 1$ or 2, $M = 1$, $k = 1$, $n = 1$.

the detection threshold (Figure 2) required to achieve the same performance using the less efficient processor. The output signal-to-noise ratio is recognized in this procedure only as a mathematical fiction describing an intermediate point in the input-to-decision chain and therefore having only limited value as a working concept.

EXAMPLES

As an interesting application of the method, and as a verification of the validity of the critical band model of audition, we may turn to measurements of the recognition differential of the ear for tones in broadband noise. According to the critical band concept, we can simulate the masking behavior of the ear by a pre-detection filter of bandwidth equal to that of the "critical band" at the frequency of the tone, an energy detector of some sort, and a low pass smoothing filter with a certain integration time. The critical bandwidth of the ear is believed[7] from studies of noise masking to be about 50 cps at a frequency of 800 cps; the integration time of the ear is similarly known to be of the order of one second at that frequency. The expression appropriate for Case III for the recognition differential for a one cycle band of noise is

$$10 \log S/N_o = 5 \log \left(\frac{dW}{T_s}\right) + |5 \log T/T_s|.$$

Using p(D) = 0.50 and assuming arbitrarily a value of p(FA)= 0.05, we find from Figure 1 that d = 3. Using W = 50 cps and T = 1.0 sec we may compute values of 10 log S/N_o as a function of pulse length T_s. The computed curve is shown in Figure 3 together with measured aural recognition differentials from the literature.[8][9][10] The ear is seen to be nearly equal in performance to the ideal energy detector. Better agreement would be had if the wider critical bandwidth suggested by more recent experiments[11] had been assumed. This agreement between theoretical curve and observed values is noteworthy in indicating the general correctness of the critical band energy-detector concept of the ear, even though various studies show[12][13] that this concept is far too simple to account for all the known facts of auditory masking. It should be stressed that a false alarm rate is seldom, if ever, referred to in the masking measurements described in the literature.

An interesting sidelight on the relation of audition and the ROC Curves is the close agreement between the "transition curves" of hearing, such as those of Schafer and Gales[14], and a curve of detection probability against detection threshold obtained from the ROC Curves at a fixed value of p(FA).

A second, and contrasting, example of the application of the method is to be the detection of radar echoes on an oscilloscope screen. During World War II, the threshold signal-to-noise requirements for radar pips were thoroughly investigated and have been reported in the well-known book of Lawson and Uhlenbeck.[15] As numerical data for comparison, we select reported measurements of input signal-to-noise ratios for single and multiple radar traces on an A-scope. Measured data of this type, as copied from Figure 8.7 of the above reference, are given in Figure 4. The ordinate is the threshold signal power required for 90% detection, in db above the noise power in a band equal to $1/\tau$, where τ is the radar pulselength. In our symbolism, this is the quantity ST_s/N_o at the 90% level of detection. The abscissa is the product of the i.f. bandwidth times the pulselength. Since the i.f. bandwidth was the smallest post-detector bandwidth employed, the reciprocal of the i.f. bandwidth is equivalent to the integration time T. Thus, the abscissa is the quantity T_s/T. The video (pre-detection) bandwidth W was 10 megacycles and the pulselength employed was 1 microsecond. Four different sets of data are plotted in Figure 4 for a single sweep and for a 3-sec. presentation time at pulse repetition frequencies of 12.5, 200, and 3200 pulses per second. These correspond to numbers of presentation, n, of 1, 37, 600 and 9600.

Selecting a value of d = 10 from Figure 2 for p(D) = 0.9 and for an assumed p(FA) of .05, we obtain the V-shaped lines plotted in Figure 4. Good agreement with the measured data is evident, especially at small values of n. However, the improvement in signal-to-noise ratio with increasing n is somewhat less than 5 log n at large values of n, implying some deterioration in the integration function of the eye for large numbers of overlapping A-scan displays.

SUMMARY

This paper is an attempt to translate, into terms useful to the underwater sound engineer, some of the implications of the ROC Curves of Peterson, Birdsall and Fox. These curves are based on a mathematical description of signals in Gaussian noise and on the concept of the optimum receiver. To predict the signal-to-noise requirements of a given system, this approach requires that two sets of parameters be specified: a pair of performance parameters, together with a number of parameters determined by the detection device, such a pulse-length and bandwidth. Once these parameters are specified, it is possible to realistically predict the detection performance of real systems. This is shown by comparisons with the measured signal-to-noise thresholds of two widely diverse detection systems. It may therefore be concluded that real detection devices do not

fall far short of the performance of the ideal receiver of the underlying theory; the ideal, optimum receiver is approximated by actual receivers when both utilize the same amount of knowledge concerning the signal and noise.

It is important to recognize that, if the noise background has Gaussian statistics, the determining factor in detectability is the amount of available knowledge concerning the signal. Once this has been determined by the system requirements, both the type of processing to be employed and the detection threshold that can be attained can be predicted. The present paper presents a method for computing this threshold for some simple detection conditions in Gaussian noise background. Although emphasizing pulsed signals, the method will apply to CW signals as well as pulses if the pulselength T_s is considered to be the observation time during which the CW signal is observed.

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FIGURES

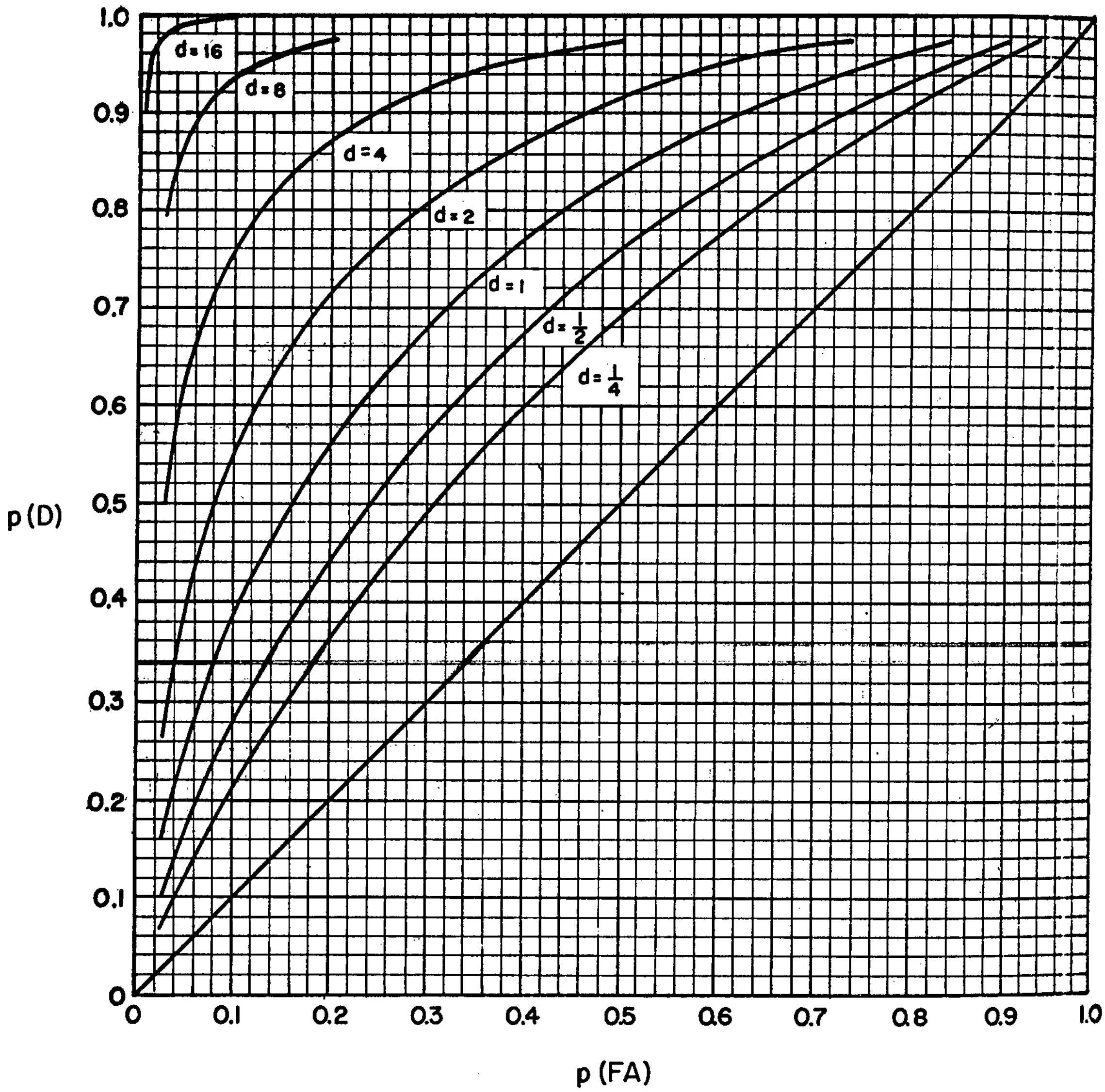
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
p (D)
d = 16
d = 8
d = 4
d = 2
d = 1
d = 1/2
d = 1/4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
p (FA)

FIG. 1

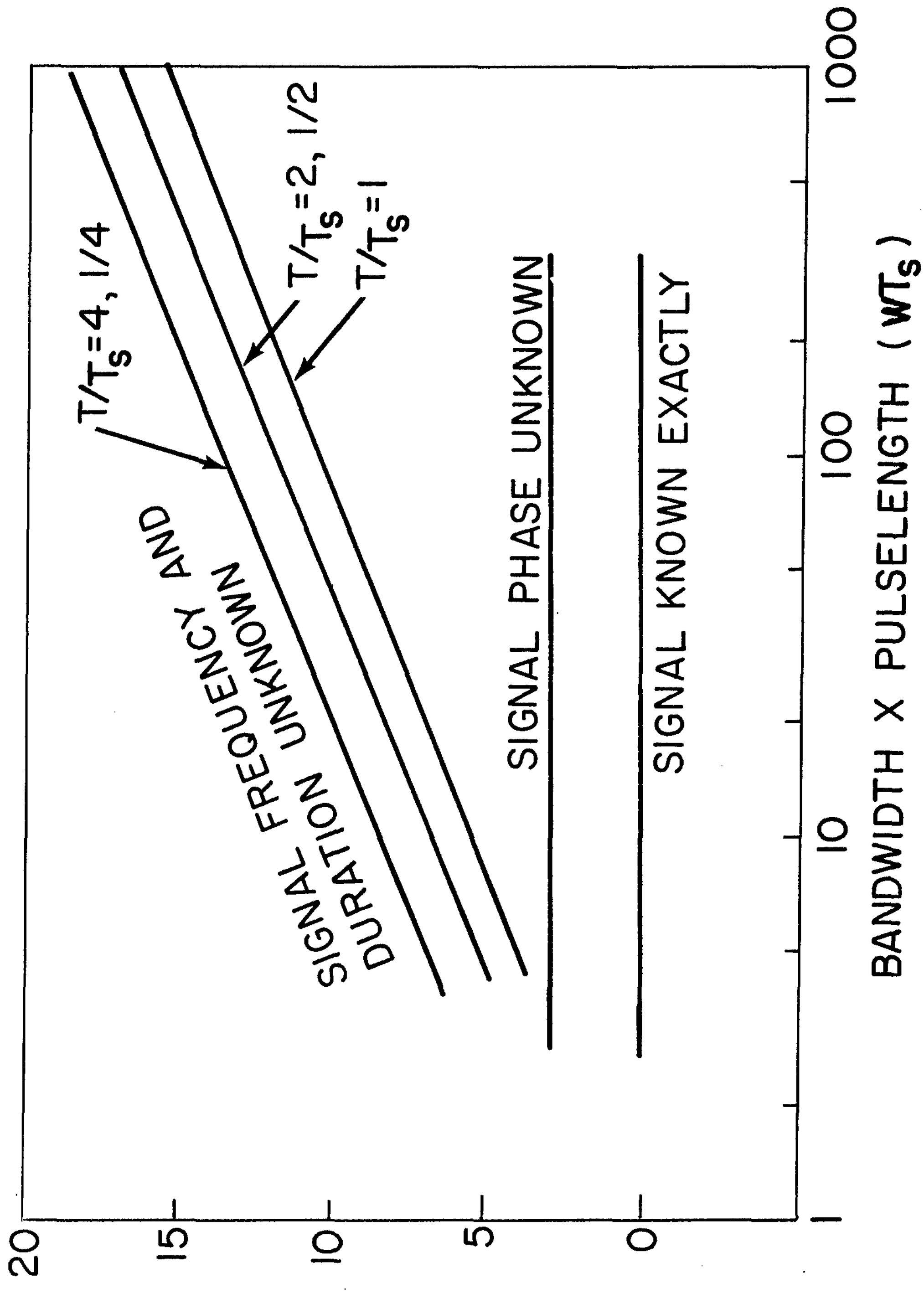

FIG. 2 INCREASE IN DETECTION THRESHOLD OVER THAT FOR A SIGNAL KNOWN EXACTLY, db

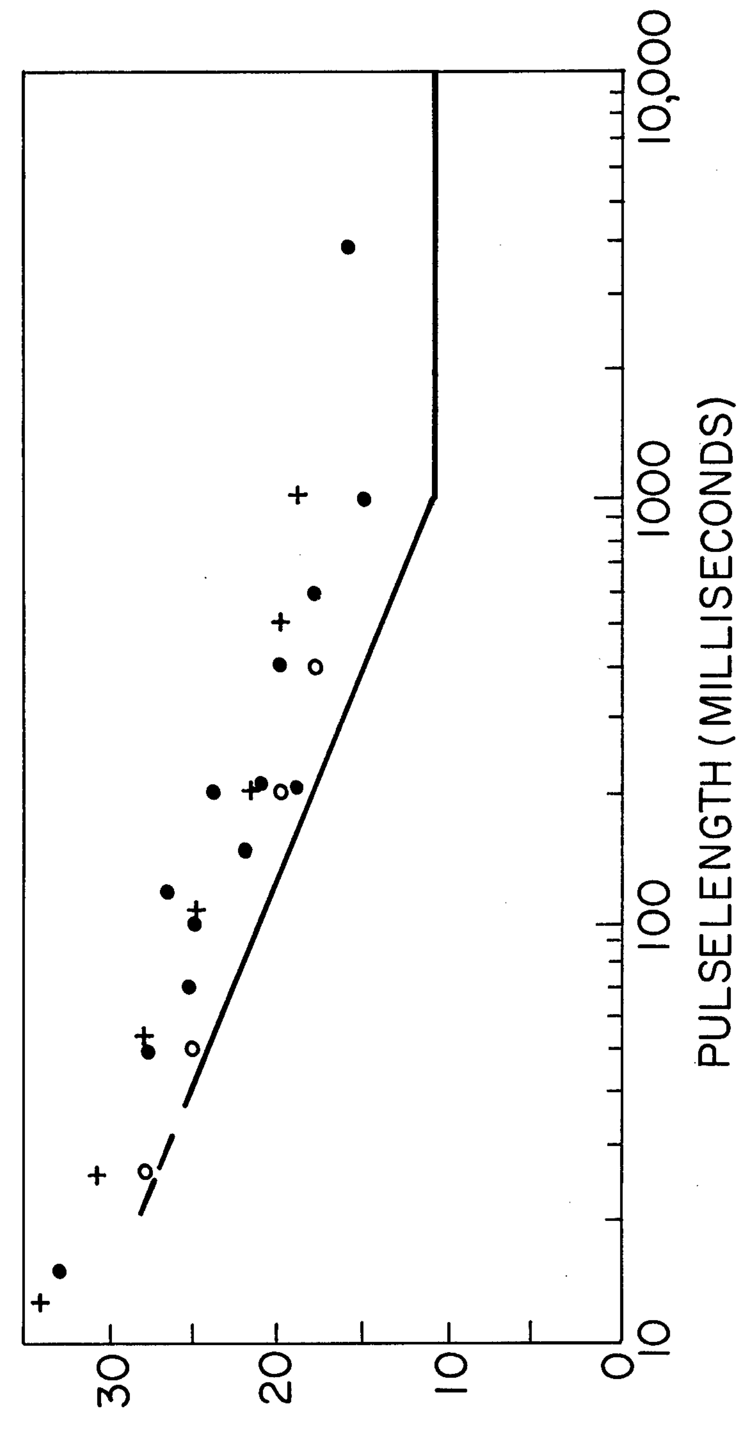

FIG. 3 RECOGNITION DIFFERENTIAL
$10 \log S/N_0$ FOR A 1 CPS
BAND OF NOISE

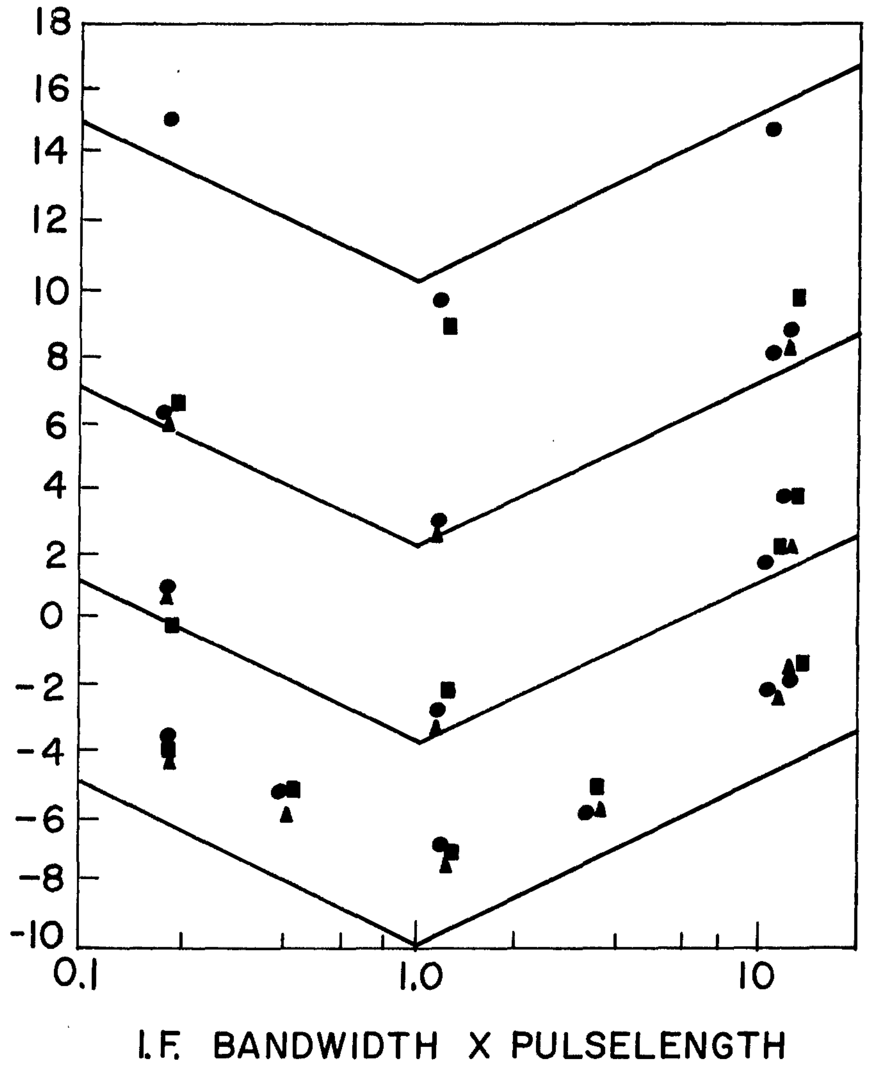

FIG. 4 THRESHOLD SIGNAL-TO-NOISE RATIO IN A BAND OF NOISE EQUAL TO $1/T_s$, db

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Attn: A. W. Phillips

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 61-164)
A SIMPLE PREDICTION METHOD FOR THE SIGNAL DETECTABILITY OF ACOUSTIC SYSTEMS (U), by R.J. Urick and P.L. Stocklin. 20 Nov. 1961. 18p. charts. Task RUDC-5E622/212-1/F001-13-005. UNCLASSIFIED

A method is given for predicting the signal-to-noise ratio to be expected for some simple receiving systems. Some sonar examples are indicated, and the validity of the method is demonstrated by comparison with measured recognition differentials for the ear, and with measured detection thresholds for A-scan radar displays.

1. Detectors - Signals
2. Detectors - Noise
3. Sonar - Echoes
4. Radar - Echoes
5. Gaussian noise

I. Title
II. Urick, Robert J.
III. Stocklin, Philip L., jt. author
IV. Project

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